

Comparison of buried sand ridges and regressive sand ridges on the outer shelf of the East China Sea

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Abstract Based on multi-beam echo soundings and high-resolution single-channel seismic profiles, linear sand ridges in U14 and U2 on the East China Sea (ECS) shelf are identified and compared in detail. Linear sand ridges in U14 are buried sand ridges, which are 90 m below the seafloor. It is presumed that these buried sand ridges belong to the transgressive systems tract (TST) formed 320–200 ka ago and that their top interface is the maximal flooding surface (MFS). Linear sand ridges in U2 are regressive sand ridges. It is presumed that these buried sand ridges belong to the TST of the last glacial maximum (LGM) and that their top interface is the MFS of the LGM. Four sub-stage sand ridges of U2 are discerned from the high-resolution single-channel seismic profile and four strikes of regressive sand ridges are distinguished from the submarine topographic map based on the multi-beam echo soundings. These multi-stage and multi-strike linear sand ridges are the response of, and evidence for, the evolution of submarine topography with respect to sea-level fluctuations since the LGM. Although the difference in the age of formation between U14 and U2 is 200 ka and their sequences are 90 m apart, the general strikes of the sand ridges are similar. This indicates that the basic configuration of tidal waves on the ECS shelf has been stable for the last 200 ka. A basic evolutionary model of the strata of the ECS shelf is proposed, in which sea-level change

is the controlling factor. During the sea-level change of about 100 ka, five to six strata are developed and the sand ridges develop in the TST. A similar story of the evolution of paleotopography on the ECS shelf has been repeated during the last 300 ka.

Keywords Buried sand ridge · Regressive sand ridge · Fine structure · Multi-beam echo soundings · East China Sea shelf

Introduction

The East China Sea (ECS) is one of the main areas of focus for the study of submarine tidal sand ridges. Zhu et al. (1984) studied the comb-like sand ridges at water depths of 60–80 m offshore of Zhejiang, China. Subsequently, Yang (1989, 2002) studied the inner structure of sand ridges in the horn-like regions of the Yangtze Estuary. Liu (1997) and Ye et al. (2004) studied the seabed characteristics on the Yangtze Shallow Shoal. Yoo et al. (2002) identified and built the sequence framework of the northern ECS based on single-channel seismic profiles. Chen et al. (2003) studied the mud ridges in the Yangtze Estuary. Liu et al. (2003) summarized the basic morphological characteristics of the sand ridges in the ECS. Li et al. (2004) sketched out the range of tidal sand ridges in the ECS region. Liao et al. (2008) studied the characteristics of sand ridges in the Taiwan Strait and forecasted their developing tendency. Some achievements have been made regarding the inner structure, classification, and formation models of buried sand ridges on the ECS shelf, based on data obtained by a joint Chinese-French cruise in 1996 (Berné et al. 2002; Liu and Xia 2004; Yin 2003; Wu et al. 2002), associated with data from borehole DZQ4 (Tang 1996). Compared the

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dating and the lithological characteristics of the borehole data of DG11, SFK-1, YQ1 and DZQ4 with the strata on the East China Sea continental shelf, Wang et al. (2014) proposed the seismic profile combining the borehole.

Some knowledge on the sequential stratigraphic study had been achieved as well. Saito et al. (1998) proposed the 5 stages of the sequential evolution since 60 ka BP based on the study of the southeast Yangtze Delta on the East China Sea continental shelf: the Stage A of sea level lowstand, the Stage B of the lowest sea level in LGM, the Stages C and D of sea level rising, and the Stage E of sea level highstand. In 50–25 ka BP, the seaward progradation of the ancient Yangtze Delta formed the sequence of the sea level lowstand (Stage A); in Stage B, the sea level rising led to the erosion of offshore seabed; in 11–8 ka BP (Stage C), the sand ridges formed on the seabed. (Berné et al. 2002) built the sequential stratigraphic model of the East China Sea continental shelf, comprising of 5 types of sedimentary strata.

The multi-beam echo sounding data have revealed that different types, strikes, and characteristics of linear sand ridges exist across the entire ECS shelf (Wu et al. 2005, 2010), and that both their area of distribution and scale of development are far greater than have been found in previous studies (see Fig. 1). Based on multi-beam echo soundings data, the crests of the sand ridges on the ECS shelf have been traced and the crest lines determined. The entire length of the crest lines of the sand ridges is about 12,279 km. The strikes of the LSR on the ECS shelf fall in a normal distribution with the center point having 155° azimuth with additional peak points at 125°, 130°, 140°, and 180° azimuth. Seven subzones, CL₁₋₁–CL₁₋₃, CL₂₋₁–CL₂₋₃, and CL₃ as listed, are delineated according to their strike features and the distribution of linear sand ridges on the ECS shelf. The general features of the distribution of four subzones, CL₁₋₁–CL₁₋₃ and CL₃ (see Fig. 1a), are similar to the paleo-estuary mouth ridges that show convergent characteristics from the southeast to the northwest. Subzones CL₂₋₁ to CL₂₋₃ are open shelf ridges (Dyer and Huntley 1999).

It has been a tendency to study the fine structure of sand ridges by using high-resolution and large-density data, such as multi-beam echo sounding data and single-channel seismic profiles (Goff et al. 1999, 2004, 2005a, 2005b; Todd et al. 1999; Todd 2005; Li and King 2007). However, some old topographic maps constructed from single-beam echo sounding data are still used to study the sand ridges, from which it is difficult to discover accurately the space–time distribution and fine structure of the sand ridges. Despite the many achievements attained in the study of sand ridges by multi-beam echo soundings or by high-resolution single-channel seismic technique, it is still rare to obtain associated results from the integration of these two methods and their data. This is especially true in the research of the fine features of sand ridges, formed at

different ages in the same region, by contrasting high-precision multi-beam echo sounding data with high-resolution and high-density single-channel seismic profiles.

The ECS shelf is a natural laboratory in which to study sand ridges because there are different types of sand ridges on the seafloor (Fig. 1a) and many buried sand ridges. The features of these sand ridges are known from the sand ridges on the North Sea shelf (Dyer and Huntley 1999). Some published study discussed the characteristics of the modern sand ridges and the buried sand ridges separately based on the multibeam bathymetric data (Wu et al. 2005, 2010) and the seismic profile (Berné et al. 2002), respectively. However, we are unaware of any published study discussing the buried and the modern sand ridges in the same study area, which is also rare on other continental shelves around the world. And there is few studies concerning the evolution from the buried sand ridges to the present regressive sand ridges.

Data and methods

Multi-beam echo sounding surveys of large areas of the ECS shelf have been carried out since the 1990s. The most advanced marine technologies have been used to survey the submarine topography, i.e., advanced multi-beam echo soundings and different global positioning systems and sub-bottom profilers. An area of hundreds of thousands of square kilometers has been surveyed and bathymetric data of almost the entire continental shelf have been collected. These data have been used to build submarine topography maps from which linear sand ridges have been identified (Fig. 1a).

In 1996, a joint Chinese-French cruise was undertaken on the ECS shelf. One of the greatest ambitions for the voyage was the desire to study the fine structure of sand ridges in the region. The author, Dr Wu, participated in this cruise as the youngest scientist. During the cruise, single-channel seismic profiles on the ECS shelf, of about 5600 km in length, were gathered by using an SIG sparker. Based on these data and borehole DZQ4, the seismic strata and faces were determined. One region (Fig. 1b) was surveyed in detail, from which 25 single-channel seismic profiles were obtained. The strata U2 and U14 in this region will be studied and compared in detail in this paper (Fig. 2).

Results

Sand ridges in U2

Reflection structures of sand ridges

In previous studies, the linear sand ridges on the ECS shelf were defined as sand ridges of U2 (Wu et al. 2002), which

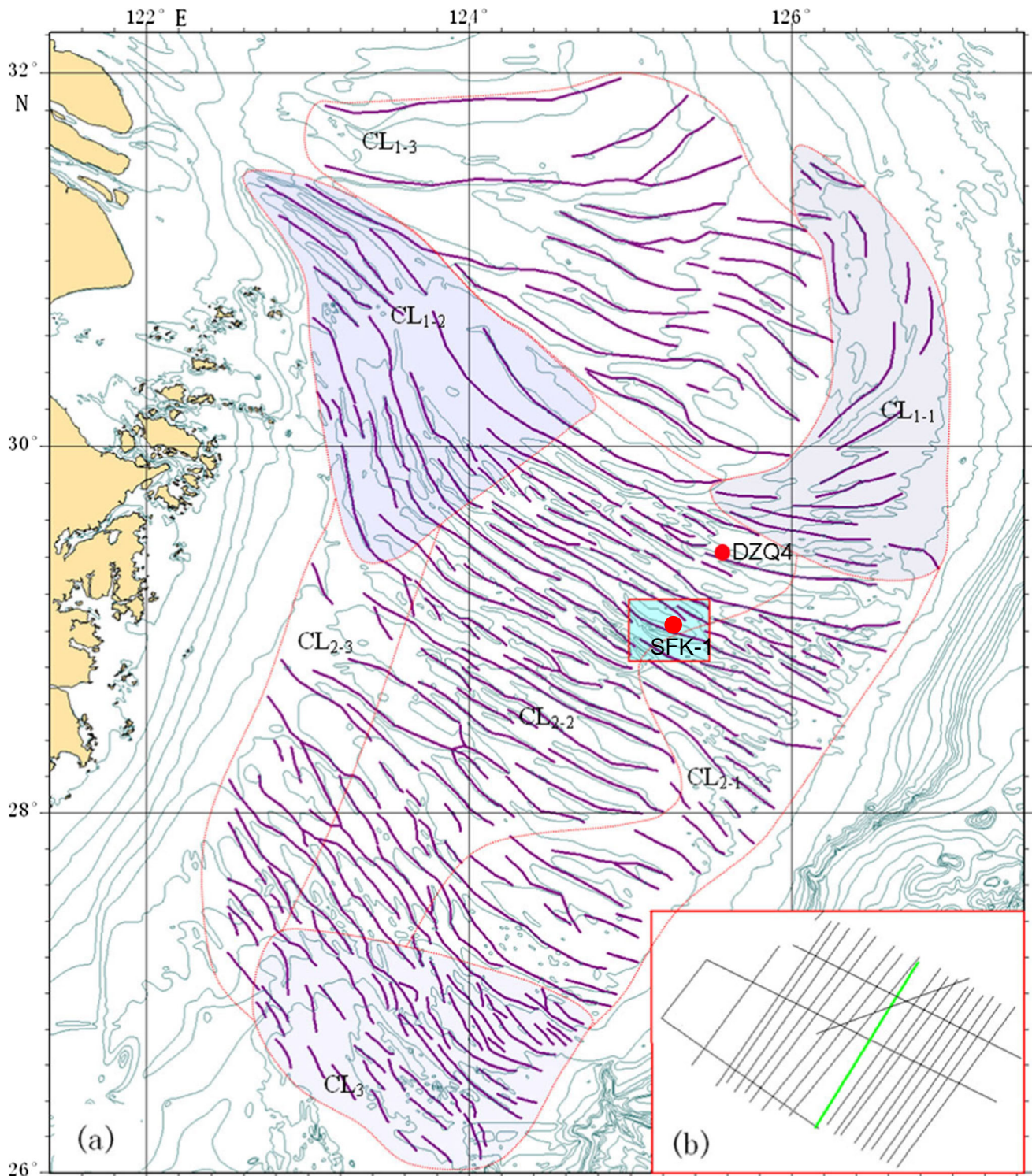


Fig. 1 **a** Spectrum and subzones of linear sand ridges on the ECS shelf. *Brown lines* represent the *crest lines* of sand ridges. *Dashed red lines* are the boundaries between subzones. The *blue-filled rectangle with a red line* is the detailed study area. **b** High-resolution single-

channel seismic profiles gathered in the study area. The *green line* is a typical seismic profile shown in Fig. 2. The *red solid circles* are the locations of the borehole, that is, the DZQ4 by Tang (1996) and SFK-1 by Wang et al. (2014)

were characterized by multi-stage compositions. Based on a typical seismic profile (Figs. 2 and 1b), U2 sand ridges can be divided into four sub-stages from A to D (Fig. 2b).

The sets of sand ridges A and C correspond to the U140a and U140b strata defined by Berné et al. (2002). Seen from the inner stratification angle and overturn relationship

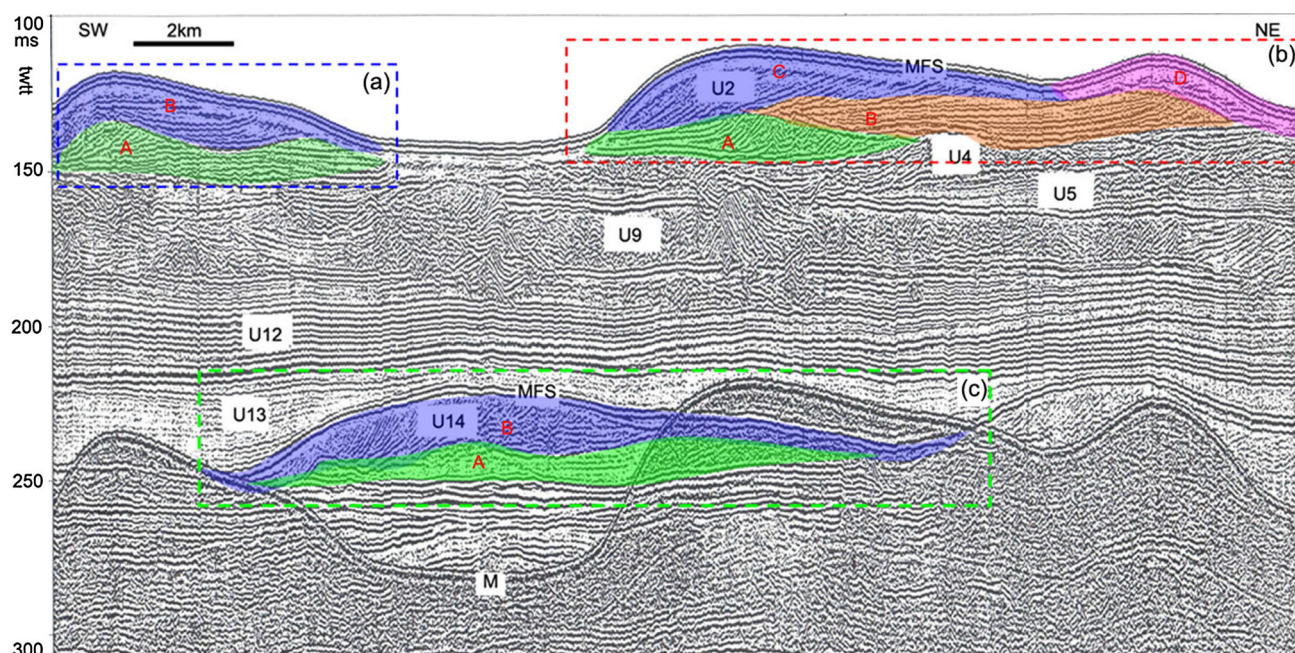


Fig. 2 Typical seismic profile whose position is shown in Fig. 1. **a–c** are sand ridges, **A–D** are sub-stages of sand ridges, **M** means multiple reflection

(Fig. 2b), sand ridges A and C are characterized by strata inclined at a large angle, whereas sand ridge B has a small angle of inclination. Sand ridge D is immature with an obscure structure, but it has a distinct boundary with the underlying sand ridge B. Sand ridge B can be regarded as the core of sand ridge D. In other words, sand ridge D is developed on sand ridge B. In Fig. 2(a), two sub-stages from A to B can be distinguished clearly. The dating of the DZQ4 (Tang 1996) and SFK-1 (Wang et al. 2014) indicates that the sand ridges in the U2 have formed since 12 ka. The dating of the bottom of the DZQ4 (~50 m in depth) is 160 ka, which has no penetrated the U14 layer of the buried sand ridges.

Three-dimensional (3D) properties of sand ridges

Six sets of regressive sand ridges (A–F) have been found from the multi-beam echo sounding data in the refined area (Fig. 3). It is obvious that sand ridge D is characterized by multi-stage compositions. According to the strikes, sand ridge D can be divided into 10 branches (Table 1). The fine characteristics of each branch are determined quantitatively based on digital model, which is built from the multi-beam echo sounding data.

According to the strikes of the sand ridges, U2 sand ridges can be divided into four groups (see Table 1): group ②, group ③, transitional group ②–③, and group ④ with strikes of 100°, 128°, 114°, and 147°, respectively. Sand ridges A, B₁, and F all belong to transitional group ②–③.

Sand ridges D₁₋₁, D₁₋₂, and D₁₋₃ all belong to group ②. Sand ridges D₃₋₁–D₃₋₄, B₂, and E all belong to group ③. Sand ridges D₄₋₁ and D₄₋₂ belong to group ④. Comparing these ridges with the U2 stage ridges, revealed by single-channel seismic profiles (Fig. 2a, b), the sand ridges of groups ③ and ④ should correspond to those in sub-stages C and D on the seismic profile, whereas the sand ridges of group ② should correspond to those in sub-stage A, which are now buried. This result could only be confirmed statistically in a small region.

The division of the stages of sand ridges across the ECS shelf should be based on additional statistical information. The scale and strikes of the sand ridges would be expected to be different, despite forming during the same period, because of the effects of tidal direction and strength at different locations. The multi-strikes of the sand ridges indicate that the direction of the paleo-tide within the region has changed many times since the last glacial maximum (LGM).

Those sand ridges that are about 10 km wide and 20 m high, such as D₁₋₁, D₁₋₂, D₁₋₃, and D₃₋₁, can be classed as trunk ridges (Figs. 4, 5). Those sand ridges that are about 5 km wide and 10 m high, can be classed as branch ridges, e.g., C, D₂, D₃₋₂, D₃₋₃, D₃₋₄, D₄₋₁, D₄₋₂, and E. Sand ridges B and F are transitional sand ridges; however, F has nearly developed into a trunk ridge. Sand ridges B and C have a tendency to merge.

In the refined region, the gradients of the southwest flanks of the ridges are generally higher than the northeast

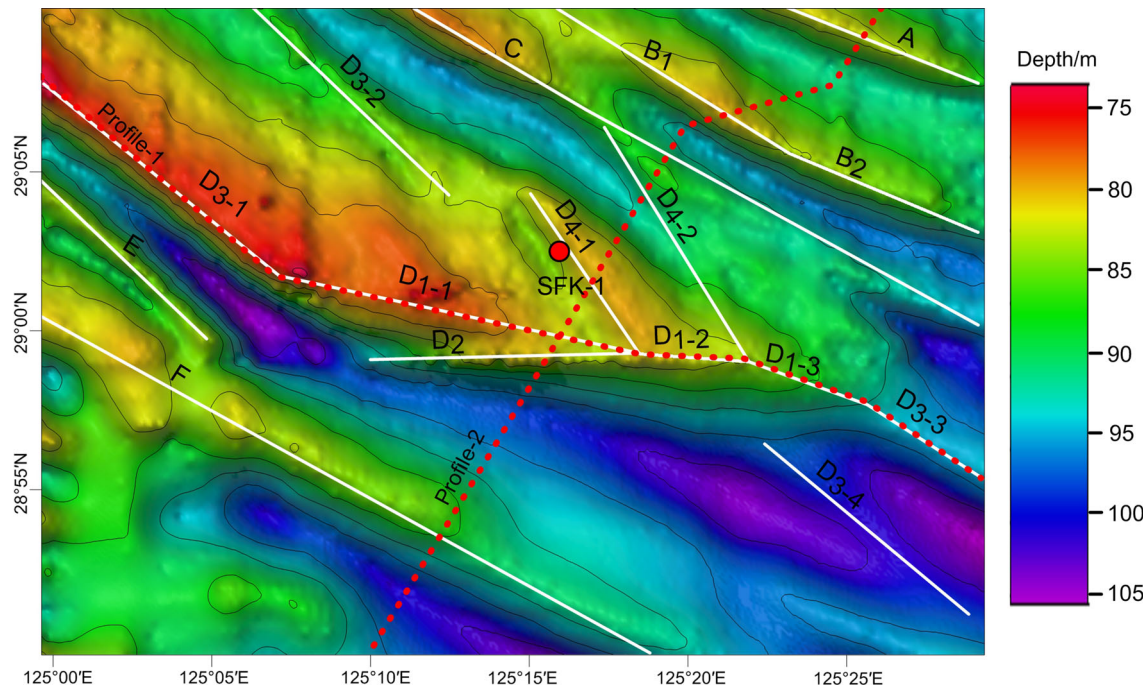


Fig. 3 Sand ridges of U2 shown by multi-beam echo soundings (position in Fig. 1), white lines are crests of sand ridges, red dot lines are topography profiles shown in Fig. 4 and 5

Table 1 Characteristic statistical table of sand ridges in stratum U2

No.	Length/km	Height/m	Width/km	Gradient/°		Trend/°	Groups
				SW	NE		
A	11	10	6	0.28	0.15	112°	②–③
B ₁	14	14	6	0.40	0.17	123°	③
B ₂	11	15	8	0.35	0.05	112°	②–③
C	34	8	5	0.17	0.1	120°	③
D ₁₋₁	18.7	22	12	0.3	0.06	102°	②
D ₁₋₂	5.5	22	13	0.19	0.07	093°	
D ₁₋₃	6.6	17	12	0.17	0.05	110°	
D ₂	14	20	5	0.28	0.03	089°	
D ₃₋₁	16	26	15	0.40	0.08	129°	③
D ₃₋₂	14.7	10	3	0.03	0.15	133°	
D ₃₋₃	7	8	8	0.14	0.06	122°	
D ₃₋₄	16	5	5	0.06	0.06	130°	
D ₄₋₁	11	10	5	0.05	0.18	146°	④
D ₄₋₂	15	6	5	0.06	0.12	149°	
E	12	15	3.5	0.16	0.40	134°	③
F	36.6	19	9	0.25	0.12	119°	②–③

flanks. The gradients of the southwest flanks are from 0.15° to 0.4° with an average value of about 0.25°, whereas the gradients of the northeast flanks are from 0.1° to 0.18° with an average value of about 0.12°. However, some sand ridges have different features; for example, the gradients of the northeast flanks of sand ridges D₃₋₂, D₃₋₄, D₄₋₁, D₄₋₂, and E are larger than those of the southwest flanks.

Proximity to the trunk ridge is the main reason for the abnormalities of the gradients, and also the cause of temporal and spatial differences in the development between the trunk ridges and branch ridges.

Sand ridge D is the most distinctive case in the refined region because it has features of multiple stages of the development of sand ridges on the continental shelf (Figs. 3,

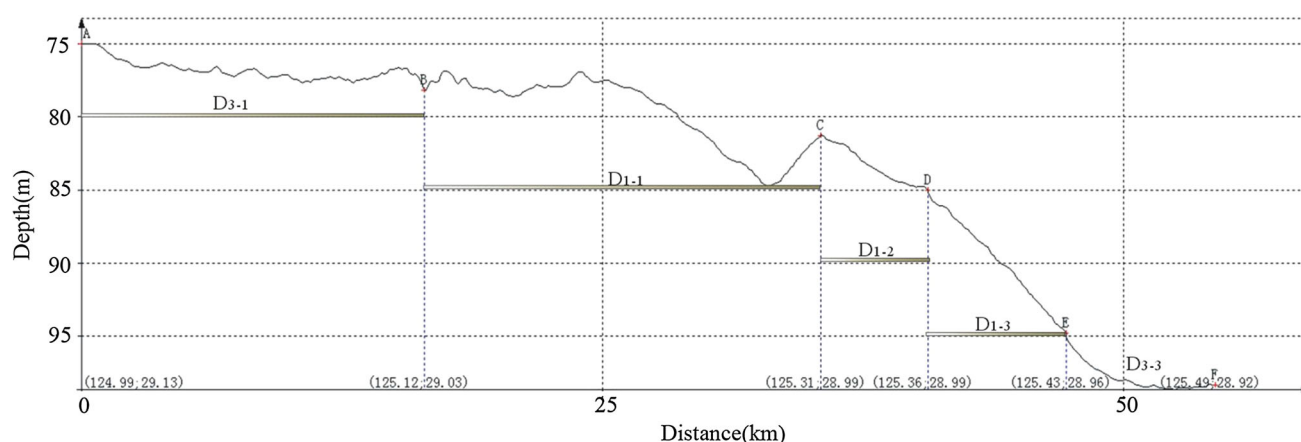


Fig. 4 Topographical profile-1 along ridge line of sand ridge D. D₁₋₁, D₁₋₂, D₁₋₃, D₃₋₁, and D₃₋₃ are branches of sand ridge D (position shown in Fig. 3)

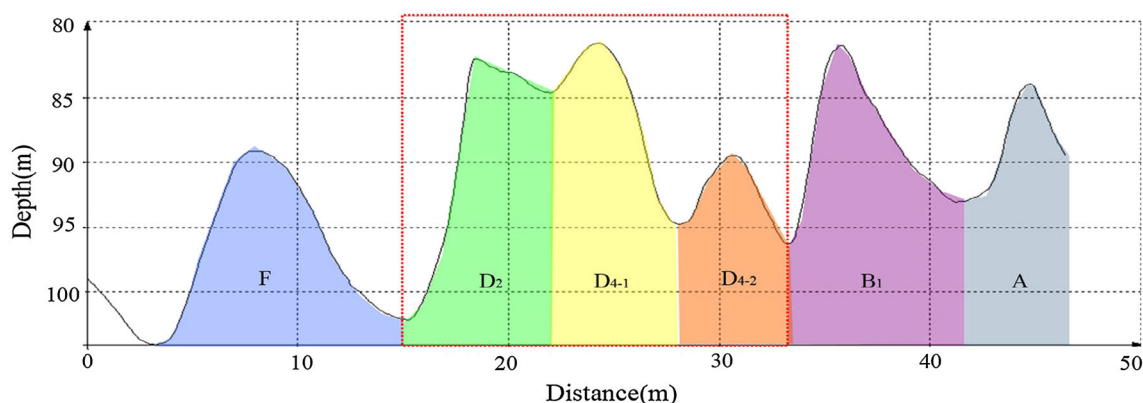


Fig. 5 Topographical profile-2 perpendicular to ridge line of sand ridge D. A and F are sand ridges, D₂, D₄₋₁, D₄₋₂, and B₁ are branches of sand ridges (positions shown in Fig. 3)

4, 5). The main branch of sand ridge D is about 55 km in length from the northwest to the southeast. It can be divided into three segments on the topographic profile (Fig. 4), which are A–B, B–E, and E–F, corresponding to branch ridges D₃₋₁, D₁₋₁–D₁₋₃, and D₃₋₃, respectively, according to the strike. It is shown on the topographic profile that the water depth at the ridge top is about 75 m in the northwest and that it increases slowly to 100 m in the southeast.

It is revealed by the changes of strike and water depth that trunk ridge D has developed over a long time. Changes of strike of a sand ridge indicate that the tidal field has differed greatly during the development of the ridge. The fluctuation of water depth at the ridge top shows that trunk ridge D was formed by the process of multi-stage superimposition. Multi-strike sand ridges are saved perfectly, which indicates that the water depth was increasing during its growth. This is in accordance with the multi-stage features of the sand ridge in U2 on the seismic profile.

Multi-stage and overlapping development features are revealed in topographical profile-2 (Fig. 5), which is taken perpendicularly across sand ridge D. Compared with the one-peak feature of sand ridges A, B, and F, the cross profile of sand ridge D (the red frame in Fig. 5) shows that it is overlain by three peaks corresponding to branch ridges D₂, D₄₋₁, and D₄₋₂. Branch ridge D₄₋₂ has a tendency to merge with sand ridge C.

Sand ridges in U14

Structure and age of sand ridges

It is shown in the high-resolution single-channel seismic profile that U14 (Fig. 2c), which has similar inner structure to U2 (Fig. 2a, b), is distributed widely 90 m below the seabed in the middle part of the ECS shelf. U14 is a typical stratum of ancient buried sand ridge with low-amplitude

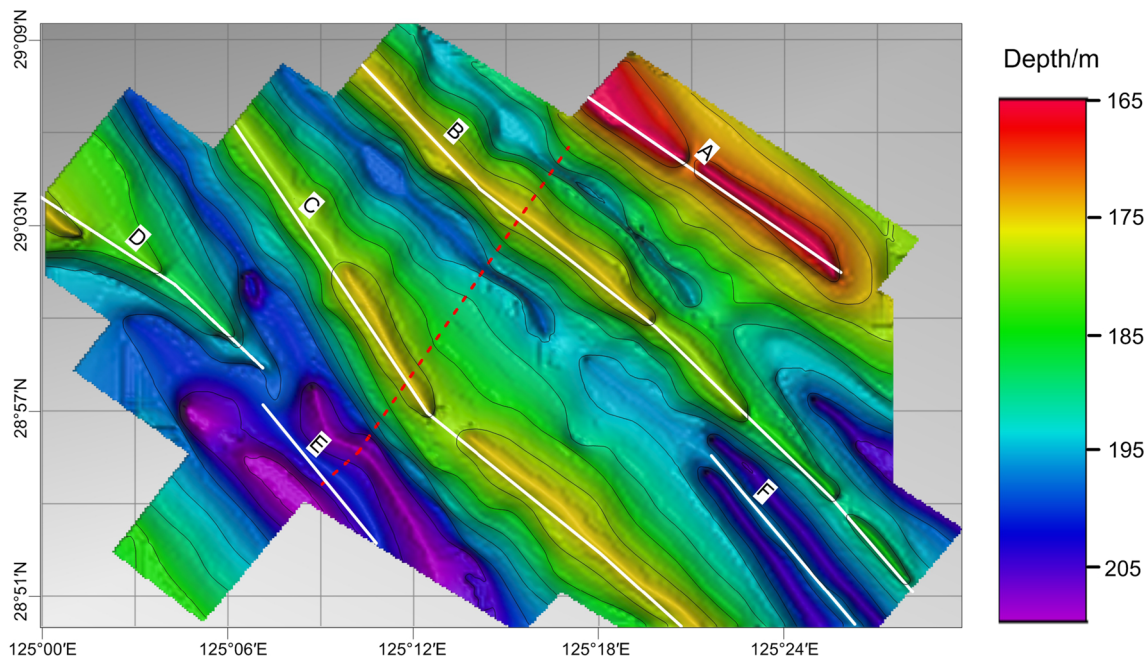


Fig. 6 Top interface depths of stratum U14 interpreted by single-channel seismic profile, *white lines* are crests of sand ridges, *red dot lines* are seismic profiles shown in Fig. 2

and high-frequency reflection. Its stratification tip to the northeast has a large angle slightly higher than that of U2. In Fig. 2c, two sub-stages from A to B are clearly distinguishable in U14. The B sub-stage sand ridge is the core of the A sub-stage sand ridge; this multi-stage feature of U14 is similar to U2.

It can be seen from the main profiles acquired in 1996 that there are sand ridges in U14 distributed extensively from latitude 124.2 to 125.8°E on the ECS shelf, but that they cannot be seen west of latitude 24.2°E because of the strong multi-waves on the profiles caused by the decreasing water depth. There are almost no sand ridges east of latitude 125.8°E because it is close to the outer margin of the ECS shelf. The analysis of the interactive relationship among the strata and the relationship between the period of strata development and sea-level change suggests that U14 should belong to the TST formed before 320–200 ka ago, whose top boundary is the maximal flooding surface (MFS) during that transgression period. According to the tendency of global sea-level change, U14 should have formed during the period of oxygen isotope 7 at 250–200 ka ago (Berné et al. 2002; Wu et al. 2002).

3-D properties of sand ridges Four trunk sand ridges (A–D) and two branch sand ridges (E and F) extending approximately from the northeast to the southwest are found in the refined study area (Fig. 6).

Buried sand ridge A in the study area is about 18 km in length and runs to 124°E in azimuth. Its width is more than 10 km and only part of it has been detected in the northeast flank of the region. The gradients of the southwest and northeast sides are about 0.29° and 0.2°, respectively. The sand ridge is about 32 m high and the buried depths of the ridge top and slot part are about 163 and 195 m, respectively.

Buried sand ridge B is about 42 km in length and extends towards 134° in azimuth, but its strike changes at the location of 125.347°E and 28.984°N, extending towards 134° in the northwestern part and towards 136° in the southeastern part. Its width is about 7 km and its height is about 27 m. The buried depths of the ridge top and slot part are approximately 173 and 200 m, respectively, changing to 175 m in the northwestern part and decreasing gradually to 200 m in the southeastern part for the sand ridge top. The gradients of the southwestern and north-eastern slopes are about 0.35° and 0.3°, respectively.

Buried sand ridge C is the largest sand ridge in the study area with a length of approximately 39 km, which can be divided into two sections at 125.2°E, 28.95°N. The strike of the southeastern part is 129°, whereas that of the northwestern section is 147°. The northern section of the sand ridge is about 12 km wide and 21 m high. The buried depth of the ridge top is about 171 m, whereas the depth of the slot part is more than 202 m. The gradient of the

southwestern slope is about 0.4° and that of the north-eastern slope is about 0.2° . The width of the southern part of the ridge is more than 15 km and it has a height of 15 m at its widest. The buried depth of the ridge top is about 175 m and that of the slot part is more than 210 m. Its two flanks are relatively smooth with a gradient of 0.3° on its southwestern slope and 0.15° on its northeast slope. The height of buried sand ridge C decreases in an undulating manner from the southeast to the northwest.

Buried sand ridge D is in the northwest of the study area and only part of it has been revealed. Buried sand ridges E and F exist among trunk ridges; they have small scale and are possibly branch ridges formed during the period of sea-level change.

Comparison of sand ridges in U2 and U14

Single-channel seismic profiles in the study area have discovered that the fine texture and dipping direction of the regressive sand ridges in U2 and U14 are similar with the inclined angle of internal reflection in U14 bigger than that in U2 (see Fig. 7).

Trunk ridges in U14 (Fig. 6) are generally more than 30 m high and about 10 km wide based on the 3D analysis of the sand ridges. They should be greater in height if the compaction function is taken into consideration. Gradients on the southwestern and northeastern flanks of the sand ridges in U14 are 0.35° and 0.2° , respectively, whereas they are 0.25° and 0.12° , respectively, for the trunk ridges in U2, and they have a height of 20 m and width of 10 km. In the same region, the gradients of the two flanks and the scale of the sand ridges in U14 are larger than in U2 (Fig. 7), whereas the flanks of the sand ridges in U2 are more asymmetric.

In the study area, six sand ridges exist in U14 with strikes from 124° to 147° and with a main direction of 125° and 140° . The main strikes of the sand ridges in U2 are 100° , 114° , 128° , and 147° , which correspond to sand ridge group ②, group ③, groups ②–③, and group ④, respectively (Table 1).

The sand ridges in U14 are mature, more linear, and with fewer branches (this may be relevant to the resolution of the surveying data). Some ridges have small twists along the strikes (Fig. 7). Sand ridges in U2 are more complex

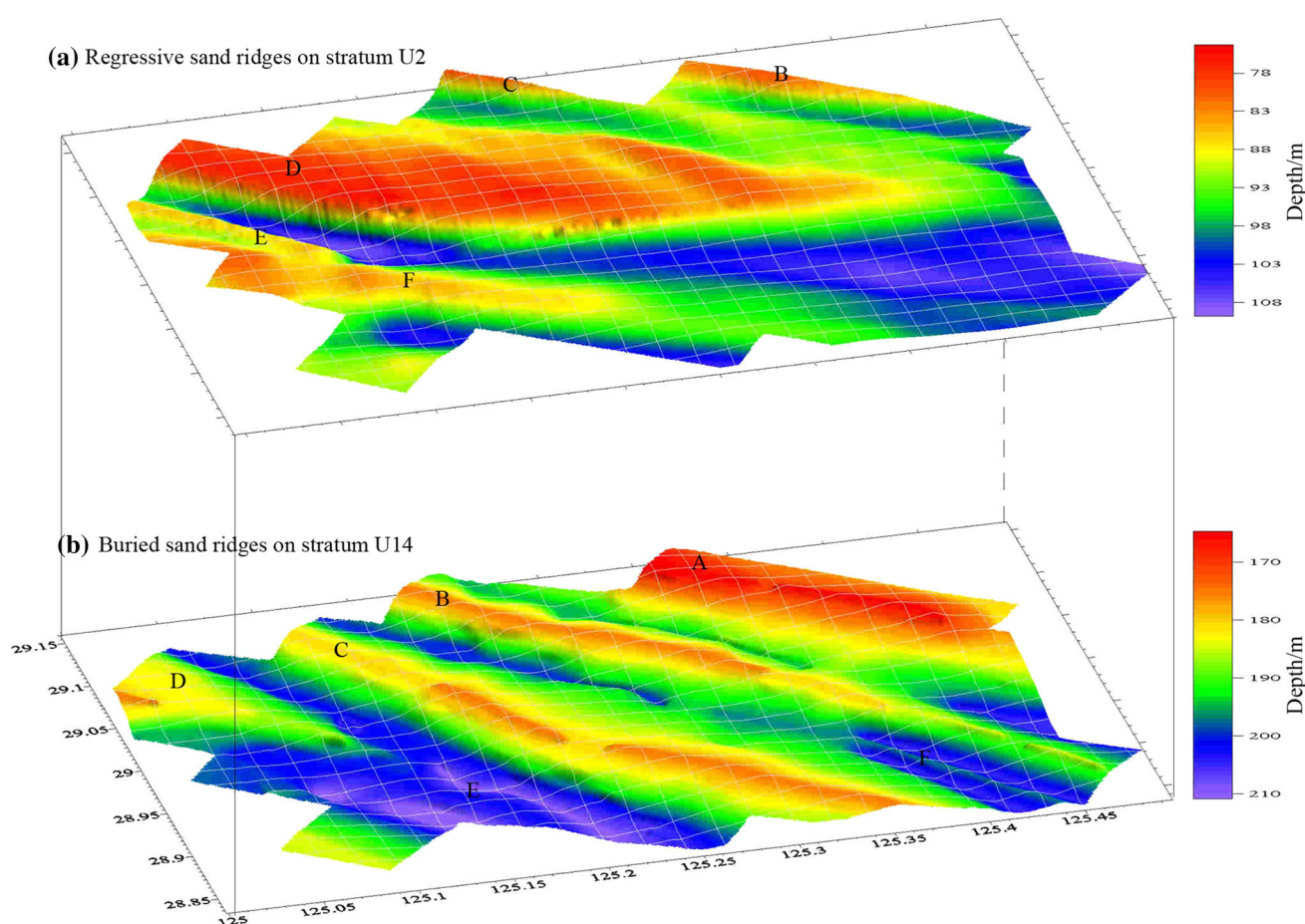


Fig. 7 Comparison of sand ridges in U2 and U14

with many linear ridges and tree- or root-like branches, and even the trunk ridges have changing strikes. Different from U14, the sand ridges in U2 show features typical of multi-stage overlapped development.

The U2 sand ridges should have been formed in the transgression period after the LGM and those of U14 should have been formed during the transgression period from 320 to 200 ka ago, based on the strength of the comparison between the curve of sea-level change and the strata on the ECS shelf (Berné et al. 2002; Wu et al. 2002). Although the ages of formation are 200 ka apart and the sequence space between U2 and U14 is 90 m, their main strikes are similar, which indicates that the general hydrodynamic environment of this region was similar during the different geological ages. U14 sand ridges exhibit larger-scale features with fewer branches, and apparent linear features, which imply that the general hydrodynamic environment of the day in the region is stable and that it remain so for a long time during the development of the sand ridges in U14. U2 sand ridges exhibit changeable strikes and have complex appearances and multiple branches, which indicate that the hydrodynamic environment in the region change during the development of the sand ridges, but that the prophasic sand ridges have not been destroyed completely by the latter tidal field. Vast masses of branch ridges prove that the development of the sand ridges have been terminated by the rapid rise of sea level.

Discussion

Correlation between the development of U2 sand ridges and sea-level change

Following the LGM, the sea level of the ECS shelf rose from its lowest level at 15 ka ago to its highest level at 7 ka ago (Jin 1992), which is in accordance with global change. The rise of sea level was not a single uniform process, but one that underwent many fluctuations (Fairbanks 1989; Liu et al. 2004). Two important melt-water pulses (MWP) of the Atlantic Ocean led to rapid changes of sea level. MWP-1A (Fairbanks 1989) occurred during the period 14.5–13.7 ka ago, and resulted in a rapid rise of sea level from 95 to 78 m, and the study area was gradually submerged. MWP-1B (Fairbanks 1989) occurred during the period 11.5–11.2 ka ago, resulting in a rapid rise of sea level from 60 to 40 m (Liu et al. 2004), and the water depth of the ECS shelf increased from 30 to 50 m. Liu et al. (2004) considered that there were two sea-level-rise events: MWP-1C that occurred 9.5–9 ka ago, and MWP-1D that occurred about 7.5 ka ago.

The underlying strata can be seen in the slot part of the sand ridges on the seismic profiles. Therefore, we can consider the slot as the bottom of one sand ridge layer and the peak as the top of the sand ridge layer. The bottom and top boundaries of layer U2, shown on the multi-beam echo sounding data, are located at the current water depth of 75 and 110 m, respectively. The bottom boundary of the A–D sub-stage sand ridges revealed on the single-channel seismic profiles are located at current water depths of about 110, 100, 95, and 90 m, respectively. There should be a close relationship between the 3D parameters of the sand ridges and the water depths in Huthnance's research (Huthnance 1982). If we consider 30 m as the most favorable water depth for the development of sand ridges (Yang et al. 2001a, 2001b) then the sea level during the time of the development of the U2 sand ridges should be from 80 to 40 m. The age of the development of the sand ridges should be 14–9.5 ka ago, according to the sea-level change curve of the ECS since the LGM. A period of stable or slightly rising sea level is beneficial to the formation of sand ridges; therefore, we deduce that two intervals among MWP-1A, MWP-1B, and MVP-1C are the main periods for the development of sand ridges within our study area. The developing process of the U2 sand ridges in the refined area is in accordance with the tendency of a four-stage development of sand ridges across the ECS shelf.

Saito et al. (1998) built a model of the development of the stratigraphic sequence with sea-level change from 80 ka ago, and suggested that the age of the development of the sand ridges on the ECS shelf started between 11 and 8 ka ago. Most researchers consider that the sand ridges on the ECS shelf were formed during the TST after the LGM, and that the only differences were the formation time. Many researchers believe that most sand ridges were stable with obvious regression features; however, some other researchers consider that the sand ridges were slightly active (Liu et al. 2007). Sand waves are the most significant indicator for the activity of sand ridges; however, it is seldom that they have been reported found on the middle or outer ECS shelf, except at the Yangtze shoal (Ye et al. 2004). It would be worthwhile in future surveys and research to determine whether the sand ridges on the ECS are active or not.

Factors influencing sand ridge development

An interrelated, complex, and mutually influential response system is constructed by many factors, such as climate, sea level, storms, tidal currents, water depth, terrain, coastline, environment, and rivers during the formation of sand ridges. Global climate change is the basic reason for the formation of sand ridges and it is the starting point of the

Domino effect. Suitable sedimentological dynamics are the fundamental reasons for the formation of sand ridges, whereas the source of supply, changes in water depth, and seafloor terrain affect the process of formation and the types of sand ridges. Storm sand ridges and tidal sand ridges reflect the differences of those sedimentological dynamic environments. A sufficient supply of material is advantageous for the formation of accumulating sand ridges, e.g., the continental shelf of the ECS (Berné et al. 2002). Poor material supply or strong dynamics may possibly lead to the formation of eroded sand ridges, e.g., offshore of the Korean peninsula (Jin and Chough 1998, 2002; Jung et al. 1998; Park et al. 2000, 2003; Shinn et al. 2007; Yoo et al. 2005). Three stages of infancy, growth, and maturation could be experienced during the development of accumulating sand ridges (Snedden and Dalrymple 1999). Shelf sand ridges, estuary sand ridges, and foreland sand ridges could be formed under the constraints of topography (Dyer and Huntley 1999). Stable or slowly ascending sea level is advantageous to the growth of sand ridges. Rapidly ascending sea level can lead to the sharp increase of shelf water depth, and to a decrease in the strength of the tidal current, which reduces the activity of sand ridge formation. Active sand ridges gradually weaken and even die under conditions of rising sea level. Sufficiently long deposition periods, persistent subsidence, and an abundant supply of material are advantageous to the formation of buried sand ridges, such as the extensive buried sand ridges 100 m below the seafloor of the ECS shelf (Berné et al. 2002; Liu and Xia 2004; Wu et al. 2002, 2005; Yin 2003).

Sequence stratigraphy evolution of ECS shelf

The Milankovitch cycle (Cyc) with a primary Cyc of 100 ka and a secondary Cyc of 40 or 20 ka leads to the global glacial-interglacial cycle with a period of approximately 100 ka. Significant changes of local sea level are known to be the response to the global glacial-interglacial oscillation, and the sea-level change determines the growth of the depositional sequences on the continental shelf (Berné et al. 2002; Saito et al. 1998; Yang et al. 2001a, 2001b; Yoo et al. 2002). The high-resolution single-channel seismic profile obtained during the joint Chinese-French cruise in 1996 (Berné et al. 2002; Liu et al. 2004; Wu et al. 2002) revealed series of strata in the sediment. Three units of strata have been discovered to refer to the three 100-ka periodic sea-level changes in the ECS region since 320 ka ago, and five or six strata have been formed during each 100-ka periodic sea-level change.

Samples from borehole DZQ4, which is 51.65 m in length and located within the study area (Tang 1996), had their ages measured by lithological, micro-paleontological, oxygen isotopic, and thermoluminescence methods. Seismic lines DS07 and DS79 cross each other near this borehole (Berné et al. 2002; Wu et al. 2002). Correlations between DZQ4 and the strata indicate that a unit of six depositional sequences was formed during the last sea-level change of the 100-ka Cyc. The force regression systems tract, the lowstand systems tract, TST, and the HST were formed during periods of sea-level fall, low sea level, low water, transgressive, and high sea level, respectively.

A model of evolution of the strata of the ECS shelf has been proposed (Fig. 8). In this model, the U1 layer, which

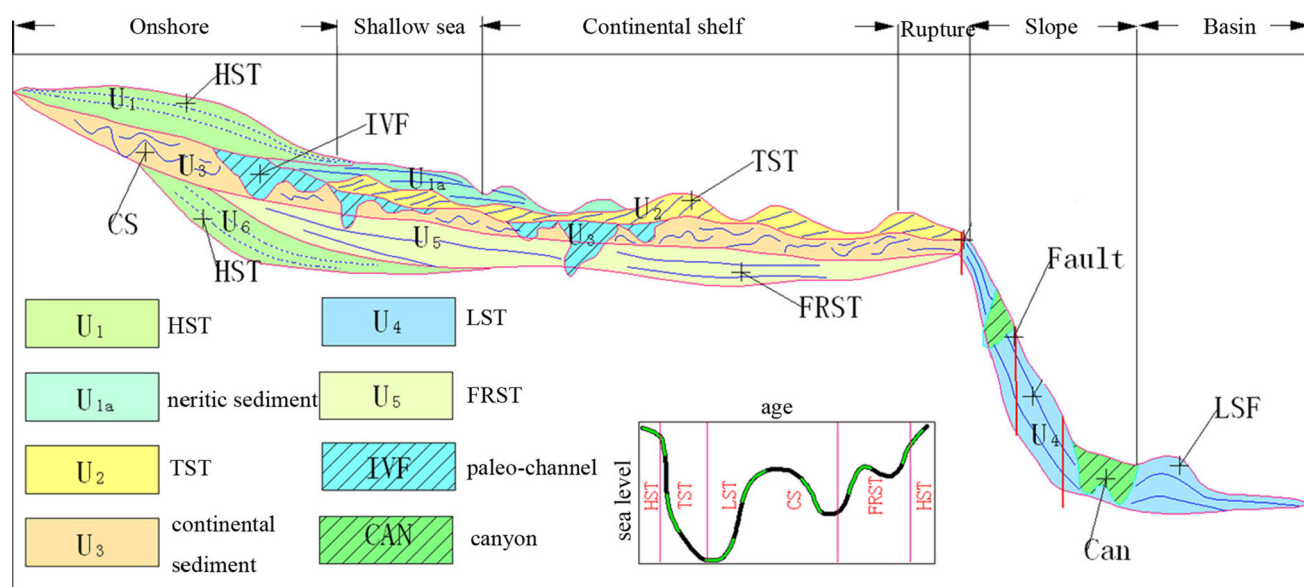


Fig. 8 Basic strata evolutionary model of ECS shelf, CS continental sediment, FRST force regression systems tract, IVF incised valleys fill, CAN canyon, LSF lowstand fan

corresponds to the Holocene sediment of the offshore ECS, is shown to be an S-shaped mud deposit wedge (Liu et al. 2006) belonging to the HST. The U2 layer, whose upper boundary is the MFS formed during the transgression period after the LGM, belongs to the TST. The U3 layer, formed at the edge of the ECS shelf, belongs to the LST. The U4 layer, whose bottom boundary is the transgressive surface of marine erosion (Berné et al. 2002), is characterized on the seismic profile by a typical V-shaped incision feature. Layers U5 and U6 have the typical depositional features of a forced regressive delta. U14 is a typical sequence of a buried sand ridge. The similarities of the features with the U2 stage sand ridges of the modern ECS shelf have proven further the periodicity of sea level and the periodicity of the paleo-environmental evolution of the ECS shelf.

Conclusions

- (1) There are ancient buried sand ridges in the U14 layer, distributed extensively 90 m below the sea-floor in the middle of the ECS shelf, which have inner structures similar to the U2 layer. The top boundary of the U14 layer is the MFS of that transgression period. It is suggested that the formation age of the sand ridges in U14 should be in the seventh oxygen isotope period, which was approximately 250–220 ka ago.
- (2) Based on the high-resolution single-channel seismic profile and multi-beam echo sounding data, 3D submarine topographical maps of two stages of the sand ridges are constructed. Their geometrical parameters are analyzed and compared. Four sub-stage sand ridges of U2 are discerned from the high-resolution single-channel seismic profile, and the four strikes of the regressive sand ridges are distinguished from the submarine topographic map based on the multi-beam echo sounding data. These multi-stage and multi-strike sand ridges are the evidence for, and the response of, the evolution of the submarine terrain with respect to sea-level change.
- (3) Combined with studies of global sea-level change, it is supposed that melt-water pulses since the LGM have influenced the development of sand ridges on the ECS shelf. The high-amplitude fluctuation of sea level in the ECS, caused by climatic change during the glacial-interglacial cycle, is the main reason for the extensively developed sand ridges existing in the shelf region.
- (4) A basic model of the evolution of the strata of the ECS shelf is proposed, in which sea-level change is

the controlling factor. During the cycle of sea-level change of approximately 100 ka, five to six strata have been developed, and the sand ridges develop during the TST. A similar story of the evolution of the paleo-topography of the ECS shelf has been repeated since about 300 ka ago.

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